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Boundary-Layer Transition on a Cooled Rough Sphere in Hypersonic Flow

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Measurements are given of the combined effects of two-dimensional roughness and surface cooling on boundary layer transition at 45° from the stagnation point on a sphere in simulated hypersonic flow. With the roughness elements at 22.5° the combined effects of roughness and cooling are represented by a single functional relation between the transition length Reynolds number and the ratio between roughness height and the displacement thickness of the boundary layer at the roughness position. The measurements cover a range of ratios of surface-to-stagnation temperature of 0.5 to 1.0 and roughness heights of 1.8×10^{-4} to 4×10^{-3} in. Comparisons are made with measurements in incompressible flow and with one datum point in hypersonic flow.

INTRODUCTION

IN Ref. 1 an experimental investigation of boundary layer transition on a cooled sphere in simulated hypersonic flow was reported. It was concluded that if the surface is smooth, transition at 45° from the stagnation point is only slightly affected by cooling in the range $0.5 < T_w/T_s < 1.0$ for the ratio of absolute temperature of the wall to stagnation value in external flow. Further, some measurements with controlled roughness indicated that the large change in transition Reynolds number observed with high cooling rates[2] could well be ascribed to the effect of the cooling on the disturbance to the flow caused by a resistance gauge on the surface. The present investigation is an extension of that reported in Ref. 1 and was designed to determine the quantitative effects of cooling and two-dimensional roughness on the transition Reynolds number $\mathrm{Re}_x = \rho_e U_e x/\mu_e$ (where ρ_e, μ_e, and U_e are, respectively, the density, viscosity, and velocity at the edge of the boundary layer and x, the distance from stagnation point).

METHOD

The experimental setup for this investigation was that described in Ref. 1, with a few modifications. Hypersonic pressure distribution over the sphere was realized by mounting the sphere in a shroud tunnel[3] through which dry high-pressure air was exhausted to the atmosphere. The sphere surface was chromium-plated to minimize erosion by dust particles remaining in the air after passage through a paper filter and several fine screens. The surface was polished with fine rouge.

Boundary layer transition was detected by the difference in pressure between a point just ahead of an upstream facing step and on the undisturbed surface at the same angular position. Chapman. Kuehn, and Larson[4] showed that this pressure difference is sensitive to the state of the boundary layer on a flat plate, and therefore the suitability of the method in these experiments on a sphere was investigated.

An upstream facing two-dimensional step, 0.02 in. high, was cemented to the surface of the sphere at the 45° position where the Mach number outside the boundary layer is near unity. The pressure difference Δp between the position just ahead of the step and a nearby position not influenced by the step was measured by means of a pressure transducer placed inside the sphere. The pressure difference coefficient, $\Delta p/q_e$, (where $q_e = \frac{1}{2}\rho_e V_e^2$) as a function of transition length Reynolds number is shown in Fig. 1 for three experiments. The variation of Reynolds number was accomplished by varying the stagnation pressure. The three records show some change in character, in that "overshooting" during transition is less pronounced in the runs involving cooling of the surface. A similar overshoot was shown in the set of measurements of Ref. 4 at subsonic speed (Mach 0.61) and was shown to be associated with transition at the free boundary in the separated flow upstream of the step. The transition is caused by the flow disturbance generated by the roughness at the upstream position. As the Reynolds number increases, the transition moves upstream along the free boundary until it reaches the laminar separation point. The turbulent boundary layer thus formed will delay flow separation and the final level of $\Delta p/q_e$ is that associated with separation of the turbulent boundary layer in-

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[1] R. Dunlap and A. M. Kuethe, J. Aerospace Sci. **29**, 1454 (1962).

[2] K. F. Stetson, J. Aerospace Sci. **27**, 81 (1960).

[3] R. Dunlap, J. Aerospace Sci. **29**, 757 (1962).

[4] D. R. Chapman, D. M. Kuehn, and H. K. Larson, NACA Rept. 1356 (1958).

duced at the step position by roughness at the 22.5° position.

The two-dimensional roughness elements consisted of wires or ribbons cemented to the surface of the sphere at 22.5° from the stagnation point.

The results were limited to a temperature ratio of 0.5 because at lower surface temperatures the cement used to secure the step to the sphere surface failed, perhaps due to differential cooling of the cooled sphere and the step. A cement that was effective near the temperature of liquid nitrogen could not be found, and the plating technique used to form the total head tube on the brass surface of the sphere used earlier[1] could not be applied to the chromium surface.

RESULTS AND DISCUSSION

The effects of two-dimensional roughness of 22.5° on transition at the 45° position on the sphere, with various degrees of cooling, are shown in Fig 2, where the transition Reynolds number Re_{x_t} is plotted versus k/δ_k^*, the ratio of roughness height to the calculated displacement thickness of the boundary layer at the roughness location. Also shown in Fig. 2 are some unpublished measurements taken previously,[1] and a measurement on a 0.5-in sphere in a shock tube.[2]

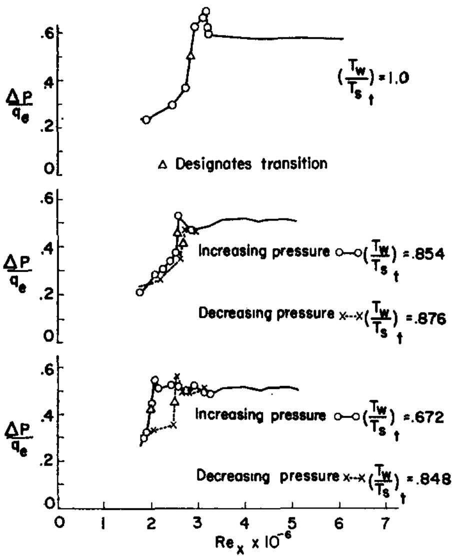

FIG. 1. Ratio of pressure rise Δp just upstream of step (at 45° position on sphere) to local dynamic pressure q_e, as a function of Re_x. Transition is assumed to occur, as indicated, at the midpoint of the rapid rise in $\Delta p/q_e$; the corresponding temperature ratios at transition are given. $k = 0.001$ in.

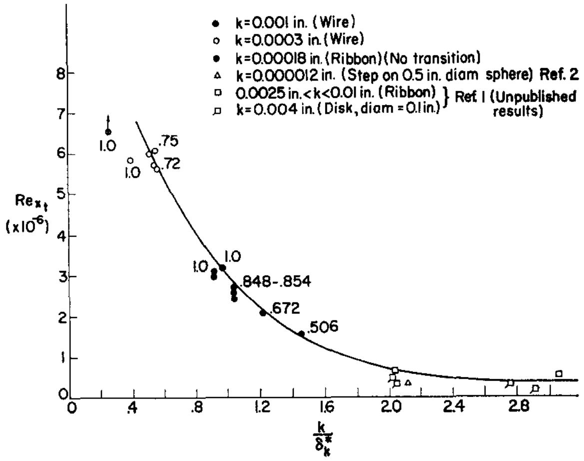

FIG. 2. Local transition Reynolds number based on distance from stagnation point Re_{x_t} vs $k/\delta^*{}_k$. Values of T_w/δ_s at transition are designated for some of the points.

Dryden[5] showed that plots with respect to the variables used in Fig. 2 effectively systematized the effect of roughness on transition on flat plates at incompressible speeds. The functional relation he found is similar to that shown in Fig. 2, but the measured transition Reynolds numbers were much lower because the boundary layer on the sphere is stable to small disturbances to much higher Reynolds numbers than is that on a flat plate.

The temperature ratios T_w/T_s are designated for the various points on Fig. 2. They vary from 0.506 to 1.0 for the current investigation, from 0.8 to 1.0 for the unpublished measurements from the previous investigation,[1] and the single point from Stetson's shock tube investigation[2] corresponds to a temperature ratio of 0.122. The two-dimensional roughness element in Stetson's experiment was taken to be the resistance element at 30° from the stagnation point; transition occurred near 45° at $\mathrm{Re}_{x_t} = 0.39 \times 10^6$. The height of the step at the resistance element was given in Ref. 2 as about 1.2×10^{-5} in. Two other experimental points, $\mathrm{Re}_{x_t} = 0.5$ and 0.72×10^6, given in Ref. 2, correspond to k/δ_k^* values of -3.5 and -1.43, at temperature ratios of 0.077 and 0.056, respectively.[6] If Re_{x_t} were plotted against δ_k^*/k instead of k/δ_k^*, these points could be included. Such a plot is not included because the scatter at large k/δ_k^* indicates that more experiments are required to fix the shape of the curve in that region.

For the smallest roughness of the present investigation, the 0.00018-in. ribbon, the point shown

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[5] H. L. Dryden, *High Speed Aerodynamics and Jet Propulsion* (Princeton University Press, Princeton, New Jersey, 1959), Division A, Vol. 5.

[6] Calculations based on the theory of C. B. Cohen and E. Reshotko [NACA Reports 1203 and 1294 (1956)] show that for temperature ratios less than about 0.1 the displacement thickness of the boundary layer is negative.

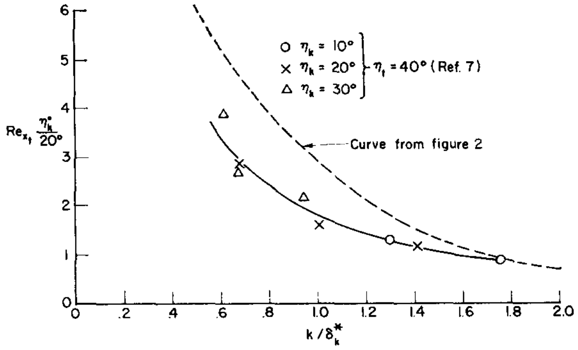

FIG. 3. Transition Reynolds numbers reported in Ref. 8 for incompressible flow over a hemisphere. Re_{x_t} is adjusted approximately to a roughness position of 20° by the factor $\eta_k{}^\circ/20^\circ$.

indicated that transition had not occurred at $\mathrm{Re}_x = 6.5 \times 10^6$. Several other observations with this roughness element indicated much lower transition Reynolds numbers. However, throughout this investigation as well as that of Ref. 1, it was the practice to accept the highest measured Re_{x_t}, on the theory that the lower values were caused by dust particles or in this case, by kinking or warping of the ribbon. Accordingly, the curve in Fig. 2 is drawn near the maximum observed values.

While there is no assurance that the combined effects of the roughness and cooling are best represented by the variables k/δ_k^* vs Re_{x_t} as used in Fig. 2, it is known that δ^* is far more sensitive to T_w/T_s than are other thickness measures[1] (boundary layer thickness δ or momentum boundary layer thickness θ). Thus k/δ_k^* will show much greater variation with T_w/T_s than will k/δ_k or k/θ_k. Many other pairs of variables were tried but all gave perceptibly greater scatter than those in Fig. 2. The single curve shown does not indicate a general result for all bodies; similar measurements by Van Driest and Boison[7] show that transition caused by two-dimensional roughness on cooled cones is described by a family of curves for different surface temperatures and Mach numbers. Effects of three-dimensional roughness are more difficult to interpret mainly because transition is triggered by single elements whose height is not predicted by a root mean square value.

Measurements by Peterson and Horton[8] with two-dimensional roughness elements on a 10-ft-diam sphere at incompressible speeds are shown in Fig. 3. Two-dimensional roughness elements were placed respectively at the 10°, 20°, and 30° positions, and values of Re_{x_t} for transition at the 40° postion were determined. The plot indicates an approximate linear inverse relationship between Re_{x_t} and η_k, the angular position of the roughness. The curve through the three sets of measurements is approximately that for $\eta_k = 20^\circ$ and is the approximate incompressible counterpart of that shown in Fig. 2 for the hypersonic flow case ($\eta_k = 22.5^\circ$, $\eta_t = 45^\circ$). The relative positions of the two curves are consistent with the fact that the laminar layer on the hemisphere will tend to be more stable in hypersonic than in incompressible flow because of the steeper favorable pressure gradient corresponding to the hypersonic distribution.

CONCLUSION

The combined effects of cooling and two-dimensional roughness on a sphere in hypersonic flow are given in Fig. 2 for $\eta_k = 22.5^\circ$, $\eta_t = 45^\circ$, and $0.5 < T_w/T_s < 1.0$. The trend of the effect of the roughness location is indicated by comparison with incompressible results[8] in Fig. 3.

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[7] E. R. VanDriest and J. C. Boison, J. Aerospace Sci. **24**, 885 (1957).

[8] J. B. Peterson, Jr., and E. A. Horton, NASA Memo 2-8-59L (1959).